

Solar Sailing for Cubesats

Patrick H. Stakem

(c) 2020

Number 35 in the Space Series

Table of Contents

Introduction	3
Author.....	4
The Physics.....	4
Radiation Pressure.....	5
Solar Minimum and Maximum.....	6
Space Weather.....	7
Spacecraft Charging.....	8
Rigging.....	9
Missions.....	9
Mission to Halley's comet.....	10
Lightsail.....	11
Nanosail-D.....	12
Near Earth Asteroid Scout.....	12
ST-9.....	13
Cubesats, a perfect Match.....	13
PiSat.....	17
NASA's Core Flight Executive, and Core Flight Software.....	19
Cubesail.....	21
Lunar flashlight.....	21
Next-Gen solar sails.....	21
Off into Deep Space.....	22
Afterword.....	23
Glossary of Terms.....	25
References.....	28
Resources.....	32
If you enjoyed this book, you might also be interested in these....	34

“There will some day appear velocities far greater than these of the planets and the projectile, of which light or electricity will probably be the mechanical agent. We shall one day travel to the moon, the planets, and the stars...”

Jules Verne, From the Earth to the Moon.

“The enormous disk of sail strained at its rigging, already filled with the wind that blew between the worlds.”

Arthur C. Clarke, *The Wind from the Sun.*

Introduction

This book will discuss the topic of sailing on the solar wind, the continuous outpouring of photons from the Sun. When these photons reflects off the sail, they give a “push” to it, exchange a small amount of momentum. In the vacuum of space, this builds up fairly quickly. As the bombardment is continuous, the velocity keeps building up as well. A solar powered craft can be steered by changing the angle of the sail to the particle stream. It can be used to fly toward the Sun by tacking, a zig-zag maneuver commonly used by sailboats. At least, solar sailing ships won't need to worry about salt water corrosion, and wet sails. But we do have to worry about “weathering” of the solar sails due to the constant flux.

Solar sails can get a spacecraft to Jupiter from Earth orbit in about 2 years. The arrival speed would be 17 km/sec, which could be reduced using Jupiter's gravity. For Saturn, it would take 3.3 years. To the Oort cloud, it would take 30 years. That's located between 5,000 to 100,000 AU. There are two clouds, a disk shaped inner one, and a spherical outer one. We don't know much about them.

At that distance, some of the material is from other than our solar system.

Author

The author has a BSEE in Electrical Engineering from Carnegie-Mellon University, and Masters Degrees in Applied Physics and Computer Science from the Johns Hopkins University. During a career as a NASA support contractor from 1971 to 2013, he worked at all of the NASA Centers. He served as a mentor for the NASA/GSFC Summer Robotics Engineering Boot Camp at GSFC for 2 years. He taught Embedded Systems for the Johns Hopkins University, Engineering for Professionals Program, and has done several summer Cubesat Programs at the undergraduate and graduate level.

Mr. Stakem has been affiliated with the Whiting School of Engineering of the Johns Hopkins University since 2007. Mr. Stakem supported the Summer Engineering Bootcamp Projects at Goddard Space Flight Center for 2 years.

The Physics

This section discusses some of the Physics behind the solar sail. How much do you need to know? Not too much. Any one can learn to handle a sail boat (I managed that myself). However, the solar sail operates in a different environment. In the first case, a boat operates in two dimensions, on the top of the plane of water (hopefully). A solar sailing craft operates in three dimensions in space. It can fly away from the Sun, or tack toward it. It can use some tricky maneuvers to go into a solar polar orbit, something that normally uses huge amounts of fuel to accomplish.

Today, it seems feasible to achieve an upper speed of one tenth that of the speed of light, using a solar sail. The solar sail uses the photons of energy streaming from the Sun. The Sun also emits charged particles. A totally different sail would be needed to use the electromagnetic radiation as a propulsion source.

Sails can generally be square, a disk, possibly spinning, the long thin blades, the helio-gyro.

Radiation Pressure

The Sun's radiation at Earth exerts about one thousandth of a gram of force over an area of 1 square meter. This is the momentum of photons of light, from the Sun. This can be reflected from a surface, causing a transfer of momentum. If we have a large enough surface, the effect is greater. The sail should be at right angles to the source of photons. If it isn't, there will be side forces as well. In addition, the further you get from the Sun, the less the pressure, due to the inverse square law. But, the pressure is constant (at a given point), always there.

Actually, we should clarify that. The Sun does go through a minimum/maximum cycle every 11 years. In addition, if the sail is eclipsed by another body coming between it and the Sun, the effect is lessened. The Solar radiation pressure at Earth is around 9 microPascals.

Solar sails are not perfect reflectors, but manage about 90% reflection. The other 10% is radiated away in both directions.

Johannes Kepler had observed that a comet's tail always faced away from the sun. He mention this in a letter to Galileo in 1610. He discussed making ships with sails "adapted to the heavenly breezes..."

James C. Maxwell in the early 1860's published his theory of electro-magnetic fields, which included the fact that light (or any radiation) exerts momentum.

In Russia, Konstantin Tsiolkovsky came up with the idea of using the pressure of sunlight to propel spacecraft. He was followed by Friedrich Zander in 1925 who published a technical paper on the topic. Bernal wrote in 1929 that a space vessel "might be blown to

the limit of Neptune's orbit." He went on to describe how the sail would be "close hauled for a tack." Einstein developed a formula for the momentum of a photon.

Solar Minimum and Maximum

The Sun's magnetic field goes through a cycle, about 11 years long. Every 11 years, the magnetic poles flip. We have no clue why. This affects surface activity, such as sunspots. By counting sunspots, we can determine if we are at a maximum or minimum. Coronal mass ejections are also effected. At Earth, ejection of charged particles at large energy's smash into the top of our atmosphere, and give us the Aurora. We define the effect of the solar cycles as *space weather*.

An extreme example of the effects of Space Weather is the Carrington Event. A large solar flare occurred in September of 1859, and was observed by British astronomer R. C. Carrington in his private observatory on his estate outside of London. Both the associated sunspots and the flare were visible to the naked eye. The resulting geomagnetic storm was recorded by a magnetograph in Britain as well. They also recorded a perturbation in the Earth's ionosphere, that we now know was caused by ionizing x-rays. In 1859, this was all observed, but not understood. The ionosphere was not known to exist at the time. Now, we know a Coronal Mass Ejection from the sun, associated with a solar storm, is first seen as an energy burst hitting the Earth, and later by vast streams of charged particles, that travel slower than the speed of light. At normal levels, these particles cause the Northern and Southern lights.

What did happen, and was not immediately associated with the solar storm, was interference with the early telegraph systems of the time. The telegraph was relatively new, and wires stretched for many miles. Think of them as long antennas. The telegraph equipment was damaged, and large arc's of electricity started fires and shocked operators. No fatalities were reported. The employees of American Telegraph Company in New York found they could

transmit messages with the batteries of their systems disconnected. The Northern lights were visible from Cuba. This was the largest such solar flare in at least 500 years ... so far.

What if such a super flare occurred today? First, we would have warning from sentinel satellites such as the Solar Dynamics Observatory, that are closer to the sun, and detect the passage of particles. They can tell us about this via radio, which travels faster than the particles. So, we would have a day or so's notice. All of our modern high-technology infrastructure would be at risk of damage, from the electrical grid to the Internet. Most of our satellites would be damaged, removing services we rely on such as long distance data communication, and navigation. It would be much better to turn everything off, and ride out the storm. Even that might not prevent major damage to networks. When is the next large solar event? Even the Astrophysicists can't tell us that. Only that it will eventually occur. Stay tuned..

Space Weather

Just like a good mariner checks the weather forecast, a solar sailer check the space weather. The Sun controls the weather in our solar system. Large solar flares can release up to 10^{25} joules of Energy. The Sun releases electrons, stripped from their atoms, the resulting ions, and intact atoms from the corona. It also releases radio waves, which, traveling at the speed of light, reach Earth 8 minutes later. The particles travel at sub-light speeds. Bright aurora's in the polar regions will be created. Stellar flares have also been observed on other stars.

When the solar wind reaches the Earth's magnetic field, it interacts with it, creating a Geomagnetic storm. There can also be proton storms from the Sun. One effect is that the upper atmosphere is heated to tens of millions of degrees Kelvin. Luckily, it is near-vacuum. Increased electromagnetic radiation from radio to Gamma Rays are also observed.

NASA's *Wind* spacecraft was launched in 1994 to study radio waves and plasma in the solar wind. It continues to operate at this writing, from the Earth-Sun L1 point. WIND is a NASA mission to study radio waves and plasma. It was headed to the L1 Lagrange point, but along the way was used to study the magnetosphere and near-lunar environment in collaboration with the SOHO and ACE spacecraft. The spacecraft is currently operation as of this writing. It has 50 years of station-keeping fuel, but the electronics will give out long before then. It is operated from Goddard Space Flight Center.

A sister mission to WIND involves the Polar satellite, studying the polar magnetosphere and aurorae. It was launched in 1996, and returned data until 2008. It conducted multi-wavelength imaging of the aurorae, measured the entry of plasma into the polar magnetosphere and the geomagnetic tail, looked at the flow of plasma to and from the ionosphere, and determined the deposition of particle energy in the ionosphere and upper atmosphere. It had eleven science instruments. These included various electromagnetic field instruments, three sensors for particles, and three imagers, for the visible, ultraviolet, and x-rays.

As a side note, the out-streaming solar wind can be used with solar sails to catch a ride, in the same way a sailboat is moved by the wind on Earth. It is even possible to tack in towards the Sun. Solar sails are lightweight, and need to be reflective. It's not a fast way to go, but it will get you there eventually, without using fuel.

The Sun has an 11 year cycle, ranging between being fairly quiet, to very stormy. Solar flares are not completely understood, and there is no good model for their prediction. Generally, we have a 2-hour window between detection, to when the storm hits Earth.

Spacecraft Charging

An issue with on-orbit spacecraft is that they are not "grounded." This can be a problem when an electrical potential develops across

the structure. Ideally, steps were taken to keep every surface linked, electrically. But, the changing phenomena has been the cause of spacecraft system failures. Where does the charge come from? Mostly, the Sun, in the forms of charged particles. This can cause surface charging, and even internal charging. Above about 90 kilometers in altitude, the spacecraft is in a plasma environment. At low Earth orbit, there is a low energy but high density of the plasma. The plasma rotates with the Earth's magnetic field. The density is greater at the equator, and less at the magnetic poles. Generally, electrons with energies from 1-100 keV cause surface charging, and those over 100 keV can penetrate and cause internal charging. As modern electronics is very susceptible to electron damage, proper management of charging is needed at the design level.

Just flying along in orbit causes an electric field around the spacecraft, as any conductor traveling through a magnetic field does. If everything is at the same potential, we're good, but if there's a difference in potential, there can be electrostatic discharge. These discharges lead to electronics damage and failure, and can also cause physical damage to surfaces, due to arcing. This has been a problem at the International Space Station.

Rigging

Rigging refers to the systems of ropes and cable that attach the sails to masts, and allow their adjustment to optimally capture the maximum wind force.

Missions

This section discusses some of the proposed and implemented solar sailing missions so far. The most ambitious and elaborate was the Japanese mission to Jupiter, with a lander to sample one of the Trojans, and bring back a sample to the mothership. It would then sail back to Earth.

Mission to Halley's comet

For the 1986 appearance of Halley's Comet, a lightsail mission was proposed by JPL. It was a 12-blade heliogyro design, to be carried to Earth orbit by the Shuttle. The mission never happened, mostly due to Shuttle delays.

The comet only comes around every 76 years, so this was an opportunity of a lifetime.

Solar sails have been used on a variety of missions. IKAROS, a JAXA mission, was the first successful solar sail mission in 2010. It left Earth orbit, and flew by Venus successfully after 6 months. It went into extended operations phase, as it was still usable.

IKAROS has a square sail, 20 meters on the diagonal, and weighing about 2 kilograms. The sail has an embedded thin film solar array. There are also embedded LCD panels in the array, whose reflectance can be individually adjusted, for attitude control. The sail was deployed by spinning at 20-25 revolutions per minute.

The next proposed Japanese lightsail mission was going to Jupiter's Trojans in the late 2020's. A Trojan is a small body (compared to its nearby planet) that shares the same orbit. By Celestial Mechanics, they are located in a stable orbit at 60 degrees ahead and 60 degrees behind the primary. These are the L4 and L5 Lagrange points. Jupiter is thought to have more than a million Trojans larger than 1 kilometer.

The mission is named *Okeanos* (see Glossary for the spiffy acronym). It is said to have a hybrid sail, with embedded solar cells powering an ion engine. The engine was to use Xenon fuel, with an Isp of 10,000 seconds. At the distance of Jupiter, the cells can provide 5 kilowatts of power. In addition, attitude control can be implemented by a series of liquid crystal panels, that adjust the reflectivity of the sail. The spacecraft masses 1,285 kg,. There is a lander that can be deployed to a target of interest. The solar sail is 1600 square meters in size. There is a possibility that the 100 kg

lander could rejoin the mothership, and carry samples back to Earth. Unfortunately, the mission was not funded.

One interesting use of solar sailing is the implementation of non-Keplerian orbits. Recall that Kepler's Laws only strictly apply in the case of the two body problem, one primary, and one smaller body orbiting the primary. We get a closed form solution for the orbit. However, in practice, the orbit is perturbed by everything else in space. In fact, if there are two similar bodies and one primary (out Sun, Earth, Moon) we cannot come up with the closed form solution. At least, not yet. So every thing affects everything else. This is known as perturbations. Kepler's laws also assume that there are no other forces than gravitational. With the small thrust of a ion engine acting as an external force, we can come up with really strange orbits, not the clean conic sections of Kepler. This could be useful in some cases. One of the more costly orbital changes in term of energy is the inclination change. It takes a large amount of fuel to accomplish. In addition, to complicate matters, the orbital inclination is entangled with some of the other 5 orbital elements. If you're not in a big hurry, the small but continuous thrust of a sail or ion engine can accomplish a fuel-less inclination change. A current conventional mission is planned, but it will travel to Jupiter, and use a slingshot maneuver with Jupiter's gravity to change inclination, then head back to the Sun.

Lightsail

Lightsail is a Cubesat mission by the Planetary Society. There were two spacecraft, the first being a non-sailing proof-of-concept. The second spacecraft has a 32 square meter sail, and is of 3U size. It was launched in June 2019. The sail, consisting of four triangular sections, deployed successfully. The spacecraft used a reaction wheel to orient the sails correctly. It tacks against the solar wind to change orbits as desired. The sail, consisting of four triangular sections, deployed successfully. Lightsail-2 was launched in June of 2019. It deployed its sails in July, and the orbit was raised by the end of the month. It should reenter after about a year on orbit.

Nanosail-D

Nanosail was a project from NASA-Ames to study the deployment of sails in space. The spacecraft was a 3-U cubesat with a 10 square meter sail. Unfortunately, the mission was lost due to a launcher error. Lightsail-2 was a follow-on mission in 2010, jointly between NASA-MSFC and Ames. It used the flight spare from the original mission. It was launched with the FAST mission in January. It initially failed to deploy, but eventually did, 2 weeks after reaching orbit. Three days after that, its sail deployed. It was in a circular orbit of 650 kilometers, at an elevation of 72 degrees. It operated until the battery power was depleted, then continued in orbit for a total of 240 days until re-entry in November of 2011.

Near Earth Asteroid Scout

NEAS is sponsored by Surrey Space Technology in the UK, and being implemented at the University of Surrey. It will be 3-axis stabilized. It is to be put in a sun-synchronous orbit around Earth.

NASA's Mariner-10 mission to Venus and Mercury in 1974 had a problem with its attitude control system and was running low on fuel. Mission control adjusted its solar panels to act as solar sails. The maneuver worked, and the spacecraft completed its Mercury fly-by. It is probably still orbiting the Sun, but hasn't been in touch for a while.

Russia launched a solar sail in early 1993 to the Russian Space Station Mir. The cosmonauts assembled the sail, moved the sailcraft to a safe distance, and released. It operated as expected, and reflected sunlight made it visible from Earth.

The Near Earth Asteroid Scout is a solar sail mission to fly to Asteroid 1991B, and hang around to get data on its composition. It will fly on the same Mars mission as the Lunar flashlight. It is to have 86 square meter sails.

ST-9

NASA proposed a lightsail mission, for the New Millennium ST-9 mission. It was to validate many of the concepts for solar sail usage. Unfortunately, the program was canceled before any launch.

A 2019 NASA mission concept was the Solar Cruiser. This was to have a 1,672 square meter sail, and orbit the Sun in a polar orbit. If approved, it will launch in 2024.

Cubesat Ultra-sail

This project, by the University of Illinois involves two 1.5 U Cubesats, and a 220 square foot sail deployed between them. The sail is a heliogyro. It was launched in 2018. A second mission is planned to be orbited in 2022. This would be much larger, with a mass of 25 kg, and a sail area of 2,500 square meters. This is a NASA SBIR Program. A follow-on will have a small controller at the tip of each 5 meter blade.

Cubesats, a perfect Match

A Cubesat is a small, affordable satellite that can be developed and launched by college, high schools, and even individuals. The specifications were developed by Academia in 1999. The basic structure is a 10 centimeter cube, (volume of 1 liter) weighing less than 1.33 kilograms. This allows multiples of these standardized packages to be launched as secondary payloads on other missions. A Cubesat dispenser has been developed, the Poly-PicoSat Orbital Deployer, P-POD, that holds multiple Cubesats and dispenses them on orbit. They can also be launched from the Space Station, via a custom airlock. ESA, the United States, and Russia provide launch services. The Cubesat origin lies with Prof. Twiggs of Stanford University and was proposed as a vehicle to support hands-on university-level space education and opportunities for low-cost space access. This was at a presentation at the University Space Systems Symposium in Hawaii in November of 1999.

Cubesats began as teaching tools, and remain in that role, although their vast numbers in orbit showed they have become mainstream. NASA has sent Cubesats to the Moon and Mars.

In what has been called the Revolution of smallsats, Cubesats lead the way. They represent paradigm shifts in developing space missions, opening the field from National efforts and large Aerospace contractors, to individuals and schools.

Cubesats can be custom made, but a major industry has evolved to supply components, including space computers. It allows for an off-the-shelf implementation, in addition to the custom build. There is quite a bit of synergy between the Amateur Satellite (Amsat) folks and Cubesats. NASA supports the Cubesat program, holding design contests providing a free launch to worthy projects. Cubesats are being developed around the world, and several hundred have been launched.

Build costs can be lower than \$10,000, with launch costs ranging around \$100,000, a most cost-effective price for achieving orbit. The low orbits of the Cubesats insure eventual reentry into the atmosphere, so they do not contribute to the orbital debris problem.

Central to the Cubesat concept is the standardization of the interface between the launch vehicle and the spacecraft, which allows developers to pool together for launch and so reduce costs and increase opportunities. As a university-led initiative, Cubesat developers have advocated many cost-saving mechanisms, namely:

- A reduction in project management and quality assurance roles .
- Use of student labor with expert oversight to design, build and test key subsystems.
- Reliance on non-space-rated Commercial-Off-The-Shelf (COTS) components .
- Limited built-in redundancy (often compensated for by the parallel development of Cubesats) .

- Access to launch opportunities through standardized launch interfaces.
- Simplicity in design, architecture and objective .

Since the initial proposal of the concept, further efforts have been made to define internal and external interfaces made by various developers of Cubesat subsystems, products, and services that have defined the Cubesat 'standard' as it is today. A core strength of the Cubesat is its recognition of the need for flexibility in the definition of standards, and since conception the standard has evolved to ensure that these design rules are as open as possible. The most significant of these further advances in definition have been for the POD systems (in order to meet launch requirements) and the modularization of the internal electronics.

The in-orbit success rate of university-led Cubesat projects (not notwithstanding launch failures) is around 50%; this is an understandable result of using the Cubesat as an education tool, where development itself is a learning process and in-orbit failure is a disappointment but should not be considered the primary focus. For projects involving significant participation of companies with experience in satellite development, all but one were a success and demonstrated the strength of the Cubesat for non-educational applications. A large number of Cubesat missions have demonstrated significant success in-orbit operations for a sustained period. All Cubesats missions have had technological objectives to some degree, be it the demonstration of devices and system architectures developed in-house, or demonstration of Non-Space-Rated (NSR) Commercial-Off-The-Shelf (COTS) component performance.

A simple Cubesat flight controller can be developed from a standard embedded computing platform such as the Arduino. The lack of radiation hardness can be balanced by the short on-orbit lifetime. The main drivers for a Cubesat flight computer are small size, small power consumption, wide functionality, and flexibility.

In addition, a wide temperature range is desirable. The architecture should support a real time operating system, but, in the simplest case, a simple loop program with interrupt support can work.

Earth imaging is a common objective for a Cubesat mission, typically achieved using a CMOS camera without any complex lens systems. As it is a critical impediment to the development of a highly capable platform for mission operations, the testing and evaluation of novel approaches for increasing downlink data rate and reliability is also a common objective. While less common than Earth imaging, real science objectives are becoming increasingly popular as recognition (primarily by NASA) of Cubesat capabilities increase and collaborations between engineering and science groups emerge.

Additional capabilities of proposed future missions either in planning or in development include: space weather monitoring, inflatable de-orbit devices, cosmic ray showers, shape memory alloys, star mapping, data relay, re-programmable computing, nano-meteorid dust, plasma probe, and multi-spectral remote sensing.

Cost reduction in these projects has been achieved through a number of mechanisms, some of which are unavailable to the conventional space industry. The lowest cost yet successful mission is reported to be estimated as under \$100,000 (although that mission was not fitted with solar arrays). A typical cost for a university project varies considerably but a very approximate estimation might be from \$50,000 to \$150,000 for launch and \$5-10,000. in parts cost per unit. Piggyback launches have been offered for free to Cubesats by launch vehicle operators and space agencies, negating the majority of launch cost.

Another important and related aspect in the design approach is that of modularity in a complete and integrated Cubesat life cycle, effectively representing a modular system of systems. The accelerated life cycle demonstrated consistently by small satellites,

and harnessed by many Cubesat developers, can be further enhanced by the application of modularity to the complete life cycle. Cubesats are ideal teaching tools for aerospace engineering students, even if they are not going to fly.

Cubesats can fly alone, as secondary payloads with other missions such as the MARCO Project to Mars, and in Swarms. The MARCO mission has 2 Cubesat fly-alongs, that separate after launch, and continue to Mars along with the primary payload.

What type of missions do Cubesat's do? Initially, they served as communications relays for Amateur radio. But, they can do essentially what any “big” satellite can do. This includes monitoring space weather, astrophysics, planetary science, or serve as technology demonstrations.

A 1-U Cubesat has a maximum weight of 1.33 kg. Cubesats are modular, and can come in multiples of 1U, like 3U, and 6U. Their low mass makes them ideal for solar sail usage.

PiSat

The PiSat is an open source NASA/GSFC design for a “Distributed Mission Test Platform.” It represents an ideal platform for prototyping Cubesat Flight software, as well as educational outreach. The PiSat defines the flight computer (ARM), a sensor suite, the enclosure and battery, and the Flight Software. It was developed by NASA/GSFC Code 582, with IRAD funding. It was developed with help from undergraduate student interns.

The Flight Computer is a Raspberry Pi (2 B+), based on the ARM architecture, and running the linux operating system or RTOS, with Code 582's Core Flight System software suite. The supported sensors include a GPS module, magnetometer, compass, accelerometer, a high definition camera, A/D converters, and a real-time clock. Data storage is provided by an SD flash memory card. It uses the Xbee peer-to-peer wireless communication. The price of the hardware components comes in around \$350, including

the printed enclosure.

Cubesats accept the PC-104 board standard (90 mm x 96 mm), and the boards are stack-able. There is no requirement to use this size board, or the standard, but there can be advantages, such as availability of interfaces.

The CFS software is reusable mission software that has already flown on many NASA missions, including the Lunar Reconnaissance Orbiter, and covers common onboard tasks. A collection of applications under the CFS includes uplink and downlink of data, attitude calculation, and support of the camera. There are a set of scripts for startup and shutdown of the system. For test or operations, there are several software choices, including the COSMOS system from Ball Aerospace. The unit is powered via USB during test and development, and by a standard lithium battery for flight.

An intern (and student of the author) integrated a ocean spectrometer into the PiSat architecture at GSFC.

Onboard Software

Flight software is a special case of embedded software. As such, it is generally more difficult to design, implement, and test. It must be treated carefully, because most of the Cubesat functionality will rely on software, and the mission success will be directly related to software.

Flight Software can be proprietary or Open Source, but almost all Cubesat onboard software is open source.

FSW has several distinguishing characteristics:

- There are no direct user interfaces such as monitor and keyboard. All interactions are through uplink and downlink.
- It interfaces with numerous flight hardware devices such as thrusters, reaction wheels, star trackers, motors, science instruments, temperature sensors, etc.
- It executes on radiation-hardened processors and

microcontrollers that are relatively slow and memory-limited.

- It performs real-time processing. It must satisfy numerous timing constraints (timed commands, periodic deadlines, async event response). Being late = being wrong.
- Besides attitude determination and control, the onboard embedded systems has a variety of housekeeping tasks to attend to.

NASA's Core Flight Executive, and Core Flight Software

The Core Flight Executive, from the Flight Software Branch at NASA/GSFC, is an open source operating system framework. The executive is a set of mission independent reusable software services and an operating environment. Within this architecture, various mission-specific applications can be hosted. The cFE focuses on the commonality of flight software. The Core Flight System (CFS) supplies libraries and applications. Much flight software legacy went into the concept of the cFE. It has gotten traction within the Goddard community, and is in use on many flight projects, simulators, and test beds (FlatSats) at multiple NASA centers, , as well as functioning in on-orbit Cubesat

The cFE presents a layered architecture, starting with the bootstrap process, and including a real time operating system. At this level, a board support package is needed for the particular hardware in use. Many of these have been developed. At the OS abstraction level, a Platform support package is included. The cFE core comes next, with cFE libraries and specific mission libraries. Ap's habituate the 5th, or upper layer. The cFE strives to provide a platform and project independent run time environment.

Small and lightweight, Cubesats are ideal for Solar Sail usage.

A spinning sail, not based on any Earth-based analog, would help keep the sail taut. The solar said could be of a circular shape, like a parachute. Another approach looked at by NASA is the heliogyro,

consisting of multiple narrow blades – looking somewhat like a helicopter. The blades would be tiltable to maximize their capture of velocity, and for steering.

A sail in a kite form could be any shape, but needs supports that minimizes flapping. In addition, we need adjustments of the sail to maximize the force. Luckily, we have a capable onboard computer that can monitor the parameters, and adjust sail tension by hauling in or letting out lines. This can be done on a continuous basis.

For the material of the sail, materials like Kapton are strong and lightweight. It needs to be highly reflective, with silver being a good yet expensive option, and aluminum is probably the next choice. Kapton has good dielectric quality, and is an insulator. Aluminized kapton is the basis of the James Webb Space Telescope sunshield. It is susceptible to mechanical wear. Similar to boat's sails, ripstops would be used to keep the sail from tearing. These usually are implemented as strips of tape or sail material. The sail and its supporting spars must limit the fluttering, an irregular motion. Carbon fiber is also a viable candidate. It is possible that the sails could be made in an orbiting facility, from more exotic materials such as lithium, magnesium, and beryllium.

Spacecraft charging is a problem in Earth orbit, and in interplanetary space. Not so much from the radiation, but from the charged particles emitted from the Sun.

Similarly, the vast number of charged particles in the solar wind could cause large electrical potential differences across the sails, causing arcing that would damage electronics.

To get anywhere, the sail equipped vehicle needs to reach escape velocity for Earth. That's around 7 kilometers per second. The sail-equipped spacecraft would circle the Earth, gaining velocity, until it can fly off on its own.

Interplanetary solar sailing is viable, even out beyond Pluto, but

the power available goes down according to an inverse square law. The trick is, numerous loops around the sun, to build up velocity.

Tacking, we could go inward towards the Sun to visit Venus and Mercury. We can also change planes with little difficulty, and visit the solar poles. This is a problem for a conventional rocket with liquid engines, due to the amount of fuel required for the plane change maneuver. But solar sails move in a 3-dimensional space, tacking their way windward to the Sun.

Cubesail

Cubesail is a proposed project by the University of Surrey (U.K.) Surrey Space Centre. It is a 3U cubesat with a 35 square meter sail. Besides maneuvering with the sail, it can be used at Cubesat end-of-life to de-orbit the mission. The cubesat's three-axis stabilized system has magnetic torquers, and a reaction wheel. The mission is scheduled to go into a sun-synchronous orbit at 800 km.

Lunar flashlight

Lunar Flashlight is a planned 6U Cubesat mission to the Moon, to search for water ice deposits. It is a joint project among JPL, Marshall Space Flight Center, and UCLA. It will be launched in 2021 as part of the Artemis-1 mission. The Flashlight has a solar sail that could also be used to illuminate areas of interest on the lunar surface. The goal is to pinpoint good landing sites for surface landers and rovers to collect and examine the ice. It will be in a lunar polar orbit, the examine the lunar polar regions. It is currently slated to have a near infrared laser to illuminate areas of interest, and an onboard spectrometer.

The Flashlight and several other Cubesats will tag along with a Mars-bound payload. Some will be dropped off at the moon, some at the asteroid belt, and some will got into deep space.

Next-Gen solar sails

Look for new sail meta-materials that alter the angle of incoming photons, effectively, a diffraction grating. The advantage is, a diffraction sail does not heat up in the interaction with the photons. Sails will get thinner, stronger, and lighter. Most proposed sails are square kilometers of microscopically thin material, with reflective metallic surfaces.

Diffraction sails don't use metallic coatings, but rather meta-materials for textiles that are used to change the angle of incoming photons, forming basically, a diffraction grating. One advantage is, the sail does not heat up, as does a simply reflective one.

Another idea that has been kicked around is that of optical. This would use a wing-shaped refractive sail which can fly in a uniform stream of light. More like a solar glider than a solar sail,

A mission was considered, to address the problem that the solar poles have never been imaged.

Off into Deep Space

Solar Sails might be a good way to accelerate to a fraction of the speed of light, the visit nearby star seasons within our lifetimes. Of course, the further the mission gets away from the Sun, the less propulsion it sees. The trick is to accelerate as much as possible. There is little or no drag – but the problem is how to slow down at the target star location – just turn around and use the sail as a break. Another option is to use large solar-powered lasers to keep the sailcraft going, augmented by a large, orbiting Fresnel lens. We don't know how to build all of this, but we're learning.

In the 1970, Robert Forward described a laser installation to provide a power source for distant light-sailers in his science fiction book, Rocheworld. You want to go really fast? How about using a solar-sailing craft at a supernova?

Now it starts getting a little complicated. We want to touch on e-sails, and m-sails, better equipped for interstellar journeys.

An electric sail uses the dynamic pressure of the solar wind as a source of thrust. But, it is constructed small wires to from an electric field, in effect, a virtual sail. The idea was suggested in 2006 in Finland. It is very different than the traditional solar sail which uses the momentum of electrons impinging on the sail. The E-sail uses an electric field to gain momentum by interacting with solar wind ions. The pressure is only about 1% of the traditional solar sail. However, it can continue to accelerate at greater distances from the Sun. An E-sail equipped nanosat, *Aalto-2*, was launched in 2017, and tested the concept for de-orbiting in 2019. It worked fine.

A magnetic sail uses a static magnetic field to deflect charged particles in a plasma, gathering momentum from the process. As opposed to a standard lightsail, these do use charged particles for momentum. They could brake against any planet with a magnetosphere.

At the Earth's distance from the Sun, the solar wind consists several million protons and electrons per cubic meter, flowing at 4-600 km/sec. The Magsail uses a magnetic field to deflect some of these, thus gaining momentum. To make the mag-sail practical, we would need a high temperature superconductor. So, Mag-sails use the plasma, and solar sails use the photons emitted from the Sun. Both methods have a generated thrust that fall off as the square of the distance from the Sun. Mag-sails can also tack.

Breakthrough Starshot is a very well funded project, to develop a fleet of 1,000 nanocraft with lightsails. These would be propelled out of our solar system by a ground based multi-gigawatt laser, and head to Alpha Centauri, achieving 20% of the speed of light. Travel time would be 20 years.

My suggestion is to have one large “mothership” with 1,000 Cubesats, going to the edge of our solar system on a standard lightsail, and by then the laser technology would be worked out. At Alpha Centauri, it is feasible to use that star's solar wind to break (I was going to say “aerobrake,” but its actually astro-brake. At this point the swarm could be released.)

Afterword

Can we go beyond our Solar System with solar sails? No problem, except we are slaved to the inverse square law of power, so we better build up velocity near to the Sun, as best we can. Freeman Dyson was a great proponent of solar sails.

We could envision a large laser facility, using solar power to direct a beam of energy towards a craft's solar sail. This might be a way to get out of our solar system, and head out to other ones. There is the problem of braking.

Glossary of Terms

1U – one unit for a Cubesat, 10 x 10 x 10 cm.

3U – three units for a Cubesat.

ACS – attitude control system.

AES - NASA's Advanced Exploration Systems

AIAA – American Institute of Aeronautics and Astronautics.

AU – astronomical unit, mean distance to the Sun, from the Earth.

BIST – built-in self test.

Bow shock – interaction of ambient plasma with magnetosphere of a planet or other object.

Capstan – a rotating machine, like a windlass, to haul on a lien,

CME – Coronal Mass Ejection (on the sun).

Cots – commercial, off the shelf.

Cp – center of pressure.

Diffractive sail – uses the principle of a diffraction grating, changing the angle of incoming photons.

EOL – end of life.

ESA – European Space Agency.

E-sail – sail using the pressure of the solar wind for propulsion

Escape velocity – the velocity required to allow an object to escape another objects gravity.

FASTSAT - Fast, Affordable, Science and Technology Satellite

Heliopause – the boundary where the Solar wind is stopped by interstellar medium. In September of 2013, the heliopause was located at 121 AU.

HGA – high gain antenna.

IKAROS - Interplanetary Kite-craft Accelerated by Radiation of the Sun.

Inclination cranking – gradual increase in orbital inclination by a lightsail.

IRU – inertial reference unit.

Isp – specific impulse, a figure of merit for propulsion systems, units of seconds.

JAXA – Japanese Space Exploration Agency.

Jibbing – on a sailing vessel, with wind coming off the stern, changing course.

JMO – Jupiter Magnetospheric Orbiter.

JPL – (NASA) Jet Propulsion Laboratory.

Kapton - a polyimide film from DuPont, stable across a wide range of temperatures.

LC – liquid crystal

LEO – low Earth orbit.

Magsail – a sail using a magnetic field to deflect charged particles from the Sun.

MSFC – (NASA) Marshall Space Flight Center.

NASA – National Aeronautics and Space Administration.

Newton – unit of force in metric system, 2.1 lbs-f.

NTRS – NASA Technical Reports Server (sti.ntrs.nasa.gov)

OKEANOS - Oversize Kite-craft for Exploration and Astronautics in the Outer Solar System.

Pa – Pascal, metric unit of pressure, 1 newton per square meter.

Plasma – a fourth state of matter, a gas of ions and free electrons.

Port – Lefts side of a vessel.

PSR – permanently shadowed regions.

PWM – pulse width modulation,

Radiation pressure – due to exchange of momentum from electromagnetic radiation. (photons).

RCD – Reflectivity control device.

Sail loading – total mass divided by the sail area.

SBIR – (NASA) Small Business Innovative Research.

SMM – Solar Maximum Mission, GSFC, 1980.

Spar – a strong pole for supporting a sail.

Starboard – right side of a vessel.

STI – (NASA) Scientific and Technical Information Program.
(sti.nasa.gov)

Sunspots – dark areas on the solar surface

Tack – turn the bow (front) of the vessel into the wind.

Torr – unit of pressure; 133.32 Pascals, 1/760 of a standard atmosphere.

UCLA – University of California, Los Angeles.

U3P – Union Pour la Promotion de la Propulsion Photonique.

WSF- World Space Foundation.

References

- Andrews, D. G. and Zubrin R. "NIAC Study of the Magnetic Sail," avail:
http://www.niac.usra.edu/files/library/meetings/fellows/nov99/320_Zubrin.pdf
- Asmar, Sami; Matousek, Steve "Mars Cube One (MarCO), First Planetary CubeSat Mission (presentation), 2014, JPL, avail: www.jpl.nasa.gov/cubesat/missions/marco.php
- Bond, Bob *The Handbook Of Sailing: A Complete Guide to All Sailing Techniques and Procedures for the Beginner and the Experienced Sailor*, 1992, ISBN-978-0679740636.
- Clarke, Arthur C. "Sunjammer," March 1964 Boys Life, also in Clarke, Arthur C. *The Wind from the Sun*, 1972, ISBN-978-0330280525.
- Datta, Lakshya Vaibhav, Guven Ugur (Ed) *Introduction to Nanosatellite Technology and Components: Applications of Cubesat Technology*, 2012, Lambert Academic Publishing, ISBN-978-3847314196.
- Engineering and Medicine, National Academies of Sciences, Division on Engineering and Physical Sciences, Space Studies Board, *Achieving Science with Cubesats: Thinking Inside the Box*, National Academies Press, 2016, ISBN-978-0309442633.
- Forward, R.L. (1984). "Roundtrip Interstellar Travel Using Laser-Pushed Lightsails". *J Spacecraft*. 21(2): 187–195, avail:
<https://arc.aiaa.org/doi/10.2514/3.8632>.
- Georgevic, R. M. (1973) "The Solar Radiation Pressure Forces and Torques Model", *The Journal of the Astronautical Sciences*, Vol. 27, No. 1.
- Gilsdter, Paul "JAXA Sail to Jupiter's Trojan Asteroids," 2017,

avail: <https://www.centauri-dreams.org/2017/03/15/jaxa-sail-to-jupiters-trojan-asteroids/>

Gilster, Paul, An Inflatable Sail to the Oort Cloud, 2008, avail: <https://www.centauri-dreams.org/2008/11/12/an-inflatable-sail-to-the-oort-cloud/>

Hollerman, William The Physics of Solar Sails, NASA/MSFC, 2002, avail: <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20030093608.pdf>.

Hughes G.W., McInnes C.R. “Solar sail hybrid trajectory optimization for non-Keplerian orbit transfers,” J. Guid. Control Dyn.25(3), pp 602–604,2002, avail: <https://arc.aiaa.org/doi/10.2514/2.4924>.

JAXA, “Small Solar Power Sail Demonstrator 'IKAROS' Successful Attitude Control by Liquid Crystal Device,” avail: https://global.jaxa.jp/press/2010/07/20100723_ikaros_e.html

Johnson, Les *Solar Sailing*, 2013, NASA Technical Reports Server, ISBN-978-1289025731. avail: <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160005683.pdf>.

Klesh, Andrew *SolWise: Sailing on Light with Interplanetary Science and Exploration*, 2012, ASIN-B01D54J472.

Lappas, Vaios, et al *CubeSail: A low cost Cubesat based solar sail demonstration mission*, Advances in Space Research, 2001, 48.11, 1890-1901.

Logsdon, Tom *Orbital Mechanics: Theory and Applications*, 1997, Wiley-Interscience, ISBN 0471146366.

Macdonal. Malcom et al, “Low-Thrust-Enabled Highly-Non-Keplerian Orbits in Support of Future Mars Exploration,” 2012,

avail: <https://doi.org/10.2514/1.52602>

Marchaj, C. A. *Sail Performance : Techniques to Maximize Sail Power*, 2002, ISBN-978-0071413107.

G Mengali, AA Quarta Non-Keplerian orbits for electric sails - Celestial Mechanics and Dynamical Astronomy, 2009, Springer, avail: <https://link.springer.com/article/10.1007/s10569-009-9200-y>

McInnes, Colin R. *Solar Sailing: Technology, Dynamics and Mission Applications*, 2004, ISBN-978-3540210627.

McInnes, Colin R. Mori, O., Matsumoto, J., Chujo, T. et al. “Solar power sail mission of OKEANOS.” Astrodyn, 2019, avail: <https://doi.org/10.1007/s42064-019-0067-8>

Mori, Osamu, et al “Direct Exploration of Jupiter Trojan Asteroid using Solar Power Sail”, (slide set) avail: http://www.jsforum.or.jp/ISSS2017/papers/slides/17087_Slide_Dr.%20Osamu%20Mori.pdf

NASA, “Solar cycle dynamics of Solar, Magnetospheric, and Heliospheric particles, and long-term atmospheric coupling,” SAMPLEX,” 2018, ISBN 978-1729002605.

Okada, T. et al “SCIENCE AND EXPLORATION IN THE SOLAR POWER SAIL OKEANOS MISSION TO A JUPITER TROJAN ASTEROID,” 49th Lunar and Planetary Science Conference 2018, avail: <https://www.hou.usra.edu/meetings/lpsc2018/pdf/1406.pdf>

Saiki, Takanao, et al “Trajectory Design for Jovian Trojan Asteroid Exploration via Solar Power Sail,” avail: http://www.jsforum.or.jp/ISSS2017/papers/paper/17086_Paper_Dr.%20Takanao%20Saiki.pdf

Sleight, Steve; Ainslie, Ben *The Complete Sailing Manual, 4th Edition*, 2017, ISBN-978-1465462572.

Starinova, O. and Chemyakina, I. "Controlling Flight from Earth to Jupiter by Solar-Sail Spacecraft in Realistic Mode," 2019, 9th International Conference on Recent Advances in Space Technologies (RAST), Istanbul, Turkey, 2019, pp. 261-265. avail: <https://ieeexplore.ieee.org/document/8767787>

Stakem, Patrick H. "Lunar and Planetary Cubesat Missions," Volume 15, Polytech Revista de Tecnologia e Ciência, avail: http://www.polyteck.com.br/revista_online/ed_15.pdf

Tsander, F. A. *Problems of flight by jet propulsion. Interplanetary flights*, 1925, NASA technical translation F-147, 1964.

Urbanczyk, Mgr., "Solar Sails-A Realistic Propulsion for Space Craft", Translation Branch Redstone Scientific Information Center Research and Development Directorate U.S. Army Missile Command Redstone Arsenal, Alabama, 1965.

Verne, Jules, *From the Earth to the Moon*, 1874, ISBN-978-1949460827.

Vulpetti, Giovanni *Fast Solar Sailing: Astrodynamics of Special Sailcraft Trajectories*, 2013, ISBN-978-9400747760.

Vulpetti, Giovanni, et al *Solar Sails: A Novel Approach to Interplanetary Travel*, ASIN-978-1493909407.

Wooster, Paul; Boswell, David; Stakem, Patrick; Cowan-Sharp, Jessy "Open Source Software for Small Satellites," SSC07-XII-3, 21st. Annual AIAA/USU, paper SSC07-XII-3, July 2007.

Wright, Jerome L. *Space Sailing*, 1992, ISBN-978-2881248030.

Resources

<https://www.planetary.org/explore/projects/lightsail-solar-sailing/what-is-solar-sailing.html>

https://www.esa.int/Education/Solar_sails

<https://www.sciencedirect.com/topics/earth-and-planetary-sciences/solar-cycle>

Small Spacecraft Technology State of the Art, NASA-Ames, NASA/TP2014-216648/REV1, July 2014.

<https://nasasearch.nasa.gov/>

Interplanetary Cubesats: Opening the Solar System to a Broad Community at Lower Cost; JPL, 2012, avail: https://www.nasa.gov/pdf/716078main_Staehle_2011_PhI_Cubesat.pdf

Chujo, Toshihiro “Liquid Crystal Device with Reflective Microstructure for Attitude Control,” 2018, avail: <https://arc.aiaa.org/doi/abs/10.2514/1.A34165>.

Hayne, P.O. et al, Lunar Flashlight: Illuminating the Moon's South Pole, avail:

<https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160004067.pdf>

LunarFlahlight - <https://techport.nasa.gov/view/14654>

Okada, Tatsuaki “Science exploration and instrumentation of the OKEANOS mission to a Jupiter Trojan asteroid using the solar power sail,” avail:

<https://www.sciencedirect.com/science/article/abs/pii/S0032063317304543>

Mori, Osamu, et al “System Designing of Solar Power Sail-craft for Jupiter Trojan Asteroid Exploration,” avail: https://www.jstage.jst.go.jp/article/tastj/16/4/16_TJSAS-D-17-00070/_article/-char/ja/

Okada, Tatsuaki, et al “OKEANOS - Jupiter Trojan Asteroid Rendezvous and Landing Mission using the Solar Power Sail,” avail:<https://ui.adsabs.harvard.edu/abs/2018cosp...42E2497O/abstract>

https://www.esa.int/Education/Solar_sails

NASA, Setting Sail for the Stars, 2000, avail:
https://science.nasa.gov/science-news/science-at-nasa/2000/ast28jun_1m/

“OPTIMIZED TRAJECTORIES TO THE NEAREST STARS USING LIGHTWEIGHT HIGH-VELOCITY PHOTON SAILS,”
avail: <https://arxiv.org/pdf/1704.03871.pdf>

https://www.nasa.gov/mission_pages/smallsts/nanosaild.html

<https://www.planetary.org/explore/projects/lightsail-solar-sailing/>

http://wiki.solarsails.info/index.php/Main_Page

Space Sailing, <http://sail.quarkweb.com/>

Wikipedia, various.

If you enjoyed this book, you might also be interested in these.

Stakem, Patrick H. *16-bit Microprocessors, History and Architecture*, 2013 PRRB Publishing, ISBN-1520210922.

Stakem, Patrick H. *4- and 8-bit Microprocessors, Architecture and History*, 2013, PRRB Publishing, ISBN-152021572X,

Stakem, Patrick H. *Apollo's Computers*, 2014, PRRB Publishing, ISBN-1520215800.

Stakem, Patrick H. *The Architecture and Applications of the ARM Microprocessors*, 2013, PRRB Publishing, ISBN-1520215843.

Stakem, Patrick H. *Earth Rovers: for Exploration and Environmental Monitoring*, 2014, PRRB Publishing, ISBN-152021586X.

Stakem, Patrick H. *Embedded Computer Systems, Volume 1, Introduction and Architecture*, 2013, PRRB Publishing, ISBN-1520215959.

Stakem, Patrick H. *The History of Spacecraft Computers from the V-2 to the Space Station*, 2013, PRRB Publishing, ISBN-1520216181.

Stakem, Patrick H. *Floating Point Computation*, 2013, PRRB Publishing, ISBN-152021619X.

Stakem, Patrick H. *Architecture of Massively Parallel Microprocessor Systems*, 2011, PRRB Publishing, ISBN-1520250061.

Stakem, Patrick H. *Multicore Computer Architecture*, 2014, PRRB Publishing, ISBN-1520241372.

Stakem, Patrick H. *Personal Robots*, 2014, PRRB Publishing, ISBN-1520216254.

Stakem, Patrick H. *RISC Microprocessors, History and Overview*, 2013, PRRB Publishing, ISBN-1520216289.

Stakem, Patrick H. *Robots and Telerobots in Space Applications*, 2011, PRRB Publishing, ISBN-1520210361.

Stakem, Patrick H. *The Saturn Rocket and the Pegasus Missions, 1965*, 2013, PRRB Publishing ISBN-1520209916.

Stakem, Patrick H. *Visiting the NASA Centers, and Locations of Historic Rockets & Spacecraft*, 2017, PRRB Publishing, ISBN-1549651205.

Stakem, Patrick H. *Microprocessors in Space*, 2011, PRRB Publishing, ISBN-1520216343.

Stakem, Patrick H. *Computer Virtualization and the Cloud*, 2013, PRRB Publishing, ISBN-152021636X.

Stakem, Patrick H. *What's the Worst That Could Happen? Bad Assumptions, Ignorance, Failures and Screw-ups in Engineering Projects*, 2014, PRRB Publishing, ISBN-1520207166.

Stakem, Patrick H. *Computer Architecture & Programming of the Intel x86 Family*, 2013, PRRB Publishing, ISBN-1520263724.

Stakem, Patrick H. *The Hardware and Software Architecture of the Transputer*, 2011, PRRB Publishing, ISBN-152020681X.

Stakem, Patrick H. *Mainframes, Computing on Big Iron*, 2015, PRRB Publishing, ISBN-1520216459.

Stakem, Patrick H. *Spacecraft Control Centers*, 2015, PRRB Publishing, ISBN-1520200617.

Stakem, Patrick H. *Embedded in Space*, 2015, PRRB Publishing, ISBN-1520215916.

Stakem, Patrick H. *A Practitioner's Guide to RISC Microprocessor Architecture*, Wiley-Interscience, 1996, ISBN-0471130184.

Stakem, Patrick H. *Cubesat Engineering*, PRRB Publishing, 2017, ISBN-1520754019.

Stakem, Patrick H. *Cubesat Operations*, PRRB Publishing, 2017, ISBN-152076717X.

Stakem, Patrick H. *Interplanetary Cubesats*, PRRB Publishing,

2017, ISBN-1520766173 .

Stakem, Patrick H. *Cubesat Constellations, Clusters, and Swarms*, Stakem, PRRB Publishing, 2017, ISBN-1520767544.

Stakem, Patrick H. *Graphics Processing Units, an overview*, 2017, PRRB Publishing, ISBN-1520879695.

Stakem, Patrick H. *Intel Embedded and the Arduino-101*, 2017, PRRB Publishing, ISBN-1520879296.

Stakem, Patrick H. *Orbital Debris, the problem and the mitigation*, 2018, PRRB Publishing, ISBN-1980466483.

Stakem, Patrick H. *Manufacturing in Space*, 2018, PRRB Publishing, ISBN-1977076041.

Stakem, Patrick H. *NASA's Ships and Planes*, 2018, PRRB Publishing, ISBN-1977076823.

Stakem, Patrick H. *Space Tourism*, 2018, PRRB Publishing, ISBN-1977073506.

Stakem, Patrick H. *STEM – Data Storage and Communications*, 2018, PRRB Publishing, ISBN-1977073115.

Stakem, Patrick H. *In-Space Robotic Repair and Servicing*, 2018, PRRB Publishing, ISBN-1980478236.

Stakem, Patrick H. *Introducing Weather in the pre-K to 12 Curricula, A Resource Guide for Educators*, 2017, PRRB Publishing, ISBN-1980638241.

Stakem, Patrick H. *Introducing Astronomy in the pre-K to 12 Curricula, A Resource Guide for Educators*, 2017, PRRB Publishing, ISBN-198104065X.

Also available in a Brazilian Portuguese edition, ISBN-1983106127.

Stakem, Patrick H. *Deep Space Gateways, the Moon and Beyond*, 2017, PRRB Publishing, ISBN-1973465701.

Stakem, Patrick H. *Exploration of the Gas Giants, Space Missions to Jupiter, Saturn, Uranus, and Neptune*, PRRB Publishing, 2018,

ISBN-9781717814500.

Stakem, Patrick H. *Crewed Spacecraft*, 2017, PRRB Publishing, ISBN-1549992406.

Stakem, Patrick H. *Rocketplanes to Space*, 2017, PRRB Publishing, ISBN-1549992589.

Stakem, Patrick H. *Crewed Space Stations*, 2017, PRRB Publishing, ISBN-1549992228.

Stakem, Patrick H. *Enviro-bots for STEM: Using Robotics in the pre-K to 12 Curricula, A Resource Guide for Educators*, 2017, PRRB Publishing, ISBN-1549656619.

Stakem, Patrick H. *STEM-Sat, Using Cubesats in the pre-K to 12 Curricula, A Resource Guide for Educators*, 2017, ISBN-1549656376.

Stakem, Patrick H. *Lunar Orbital Platform-Gateway*, 2018, PRRB Publishing, ISBN-1980498628.

Stakem, Patrick H. *Embedded GPU's*, 2018, PRRB Publishing, ISBN- 1980476497.

Stakem, Patrick H. *Mobile Cloud Robotics*, 2018, PRRB Publishing, ISBN- 1980488088.

Stakem, Patrick H. *Extreme Environment Embedded Systems*, 2017, PRRB Publishing, ISBN-1520215967.

Stakem, Patrick H. *What's the Worst, Volume-2*, 2018, ISBN-1981005579.

Stakem, Patrick H., *Spaceports*, 2018, ISBN-1981022287.

Stakem, Patrick H., *Space Launch Vehicles*, 2018, ISBN-1983071773.

Stakem, Patrick H. *Mars*, 2018, ISBN-1983116902.

Stakem, Patrick H. *X-86, 40th Anniversary ed*, 2018, ISBN-1983189405.

Stakem, Patrick H. *Lunar Orbital Platform-Gateway*, 2018, PRRB

Publishing, ISBN-1980498628.

Stakem, Patrick H. *Space Weather*, 2018, ISBN-1723904023.

Stakem, Patrick H. *STEM-Engineering Process*, 2017, ISBN-1983196517.

Stakem, Patrick H. *Space Telescopes*, 2018, PRRB Publishing, ISBN-1728728568.

Stakem, Patrick H. *Exoplanets*, 2018, PRRB Publishing, ISBN-9781731385055.

Stakem, Patrick H. *Planetary Defense*, 2018, PRRB Publishing, ISBN-9781731001207.

Patrick H. Stakem *Exploration of the Asteroid Belt*, 2018, PRRB Publishing, ISBN-1731049846.

Patrick H. Stakem *Terraforming*, 2018, PRRB Publishing, ISBN-1790308100.

Patrick H. Stakem, *Martian Railroad*, 2019, PRRB Publishing, ISBN-1794488243.

Patrick H. Stakem, *Exoplanets*, 2019, PRRB Publishing, ISBN-1731385056.

Patrick H. Stakem, *Exploiting the Moon*, 2019, PRRB Publishing, ISBN-1091057850.

Patrick H. Stakem, *RISC-V, an Open Source Solution for Space Flight Computers*, 2019, PRRB Publishing, ISBN-1796434388.

Patrick H. Stakem, *Arm in Space*, 2019, PRRB Publishing, ISBN-9781099789137.

Patrick H. Stakem, *Extraterrestrial Life*, 2019, PRRB Publishing, ISBN-978-1072072188.

Stakem, Patrick H. Submarine Launched Ballistic Missiles, 2019, ISBN-978-1088954904.

Patrick H. Stakem, *Space Command*, Military in Space, 2019, PRRB Publishing, ISBN-978-1693005398.

2020 Releases

Exploration of Lunar & Martian Lava Tubes by Cube-X.

Robotic Exploration of the Icy moons of the Gas Giants.

Hacking Cubesats.

History & Future of Cubesats.

Robotic Exploration of the Icy Moons of the Ice Giants.